A LONG-TERM PERSPECTIVE ON GLACIAL EROSION

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ABSTRACT

A rough estimate of glacial erosion in the Precambrian basement is related to the total denudation of bedrock since its formation in the Proterozoic. The basis for the calculations is reference to surfaces of different age. Glacial erosion is responsible for merely polishing the northern shields. Major denudation occurred during the Proterozoic and amounted to tens of kilometres. During long periods the basement was protected by Palaeozoic cover rocks. It was re-exposed successively during the Mesozoic and Tertiary with denudation amounting to 600 m at the most. Glacial erosion can generally be counted in tens of metres though with great variations. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

In formerly glaciated parts of the world the marks of glacial erosion are obvious. As a consequence, it has long been thought that the time-scale for relief development is short, i.e. that the landforms of today are wholly of Quaternary origin. That such opinions have been widespread seems to be a result of limited interest in long-term landform development since the 1950s and the resulting unfamiliarity with the genesis of the main landforms on formerly glaciated shields. Limited glacial erosion of the northern shields was argued long ago (Pumpelly, 1879; Nathorst, 1879; Chalmers, 1898; Taylor, 1911; Thwaites, 1934), based mainly on the occurrence of remnants of preglacial saprolites. This view was also maintained by researchers working in southern Sweden during the late 1930s to the early 1960s (e.g. Björnsson, 1937; Mattsson, 1962), who pointed to the many preglacial relief features as well as imprints on the same rock surfaces from several ice overridings. During the 1970s White (1972) argued for deep glacial erosion of the northern lands, but this was challenged by Sugden (1976, 1978). White noted that the northern shields coincide with the extension of the Pleistocene ice sheets and thought that the central seas (the Hudson Bay and the Gulf of Bothnia) were formed by deep glacial erosion in the crystalline basement. The slopes bordering the seas (the inward slopes) he interpreted as formed by glacial erosion. However, both Hudson Bay and the Gulf of Bothnia are old tectonic structures filled with several kilometres of Proterozoic and Early Palaeozoic sedimentary strata. The extremely flat surfaces on the inward slopes are the exhumed sub-Cambrian/Ordovician surfaces, which have been well known in Fennoscandia (here mainly sub-Cambrian) since the early part of this century (Högbom, 1910). Their existence and relation to the cover rocks have been confirmed in many later studies (Lidmar-Bergström, 1996). Lately, researchers in Sweden and Canada have discovered landforms of glacial deposition which remained virtually untouched by the passage of the last ice sheet (Lagerbäck, 1988a,b; Dyke, 1993; Kleman, 1994). Even if the glacial overprinting is obvious in most parts of the Scandinavian landscapes, the basic forms are much older (Lidmar-Bergström, 1982, 1988, 1995). Even forms of medium and small size can be due to preglacial processes (Lidmar-Bergström, 1989). Clearly, this weight of evidence contradicts White's view of deep glacial erosion.

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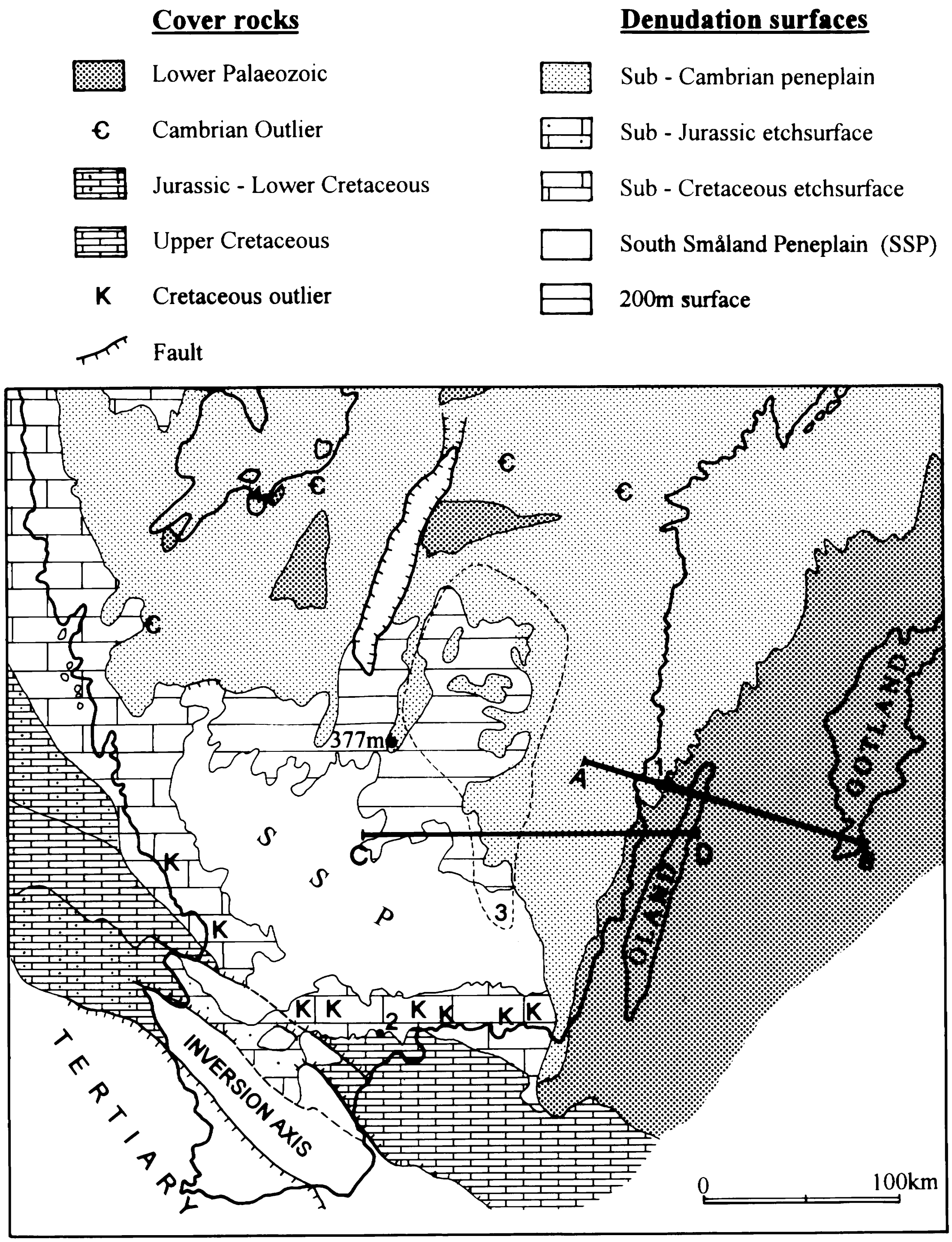

Figure 1. The South Swedish Dome (SSD) with palaeosurfaces, covers and sites. Generalized from Lidmar-Bergström (1994). (1) The island of Jungfrun. (2) Ivö island. (3) Area with abundant remnants of gravelly saprolites. (4) Kinnekulle.

PALAEOSURFACES

Basically three types of palaeosurface make up the relief of the Fennoscandian shield (Lidmar-Bergström, 1994). Two of these are exhumed, namely the sub-Cambrian peneplain and the sub-Mesozoic etch-surfaces. The third type describes plains with residual hills, which have developed during the Tertiary. The south Swedish Dome (SSD) has turned out to be a key area for reconstructions of the stages in the relief evolution, since basement rocks emerge from below covers of different age (Cambrian, Jurassic, Upper Cretaceous). The exhumed surfaces are inclined and cut by a subhorizontal surface, the South Småland Peneplain (SSP), which is thus younger, namely of Tertiary age (Figure 1; Lidmar-Bergström, 1982, 1988). The palaeosurfaces have diagnostic relief features and remnants of saprolites with different characteristics (Lidmar-Bergström *et al.*, 1996).

The sub-Cambrian peneplain

Basement surfaces exhumed from below the Cambrian cover at the foot of Kinnekulle (Figure 1) are similar to roche moutonnées, but retain patches of Cambrian cover on all sides (Högbom and Ahlström, 1924; Mattsson, 1962). In direct contact with the overlying cover rocks, the rock surfaces are weathered and there are

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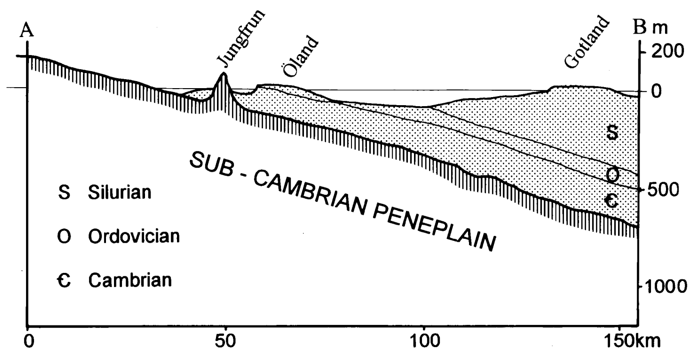

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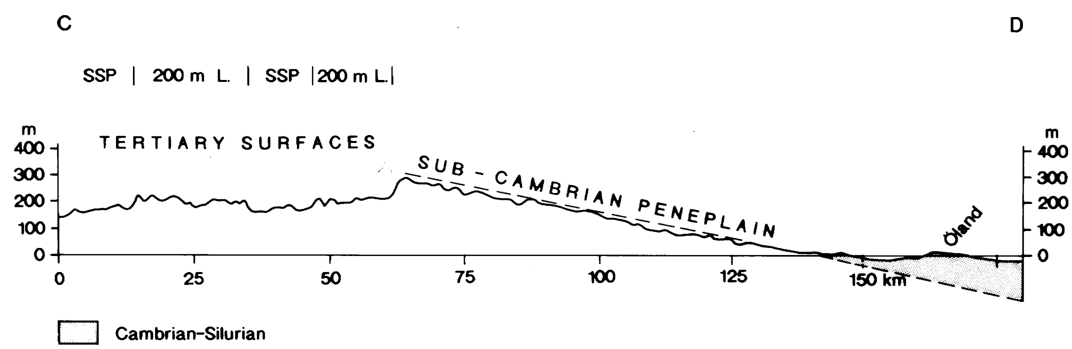

Figure 2. (a) The island of Jungfrun, a residual hill on the sub-Cambrian peneplain. For location of profile see Figure 1. Geology from Kornfält and Larsson (1987), and exhumed morphology from contour maps. (b) The exhumed sub-Cambrian peneplain with its western erosional slope and the Tertiary surfaces. For location of profile see Figure 1. The erosional scarp and the small amount of erosion below the sub-Cambrian surface also indicate very faint glacial erosion. Profile redrawn from Lidmar-Bergström (1988).

certainly no exhumed glacial features. Shallow kaolinization (max. 5 m) is often encountered below the Cambrian cover (Elvhage and Lidmar-Bergström, 1987), but is commonly eroded outside the cover remnants. The exhumed sub-Cambrian peneplain makes up the present relief over large parts of central and eastern Sweden (Rudberg, 1954; Lidmar-Bergström, 1994). The relative relief in the well preserved parts amounts to 20 m. Exceptionally, residual hills stand on the peneplain, such as the island of Jungfrun, which reaches 160 m above the peneplain level (Figures 1 and 2a). The peneplain was the result of denudation after a long period with stable tectonic conditions. Shallow etching and sheetwash were probably the most important processes in the final moulding of the surface. The sub-Cambrian peneplain is part of a primary peneplain which was once formed across most of the Fennoscandian shield (Elvhage and Lidmar-Bergström, 1987; Lidmar-Bergström, 1996). This primary peneplain was successively covered by Vendian, Cambrian and Ordovician sediments and protected from erosion by a thick Palaeozoic cover over a long period (Lidmar-Bergström, 1996).

The sub-Mesozoic etch-surfaces

Parts of the primary peneplain were re-exposed and experienced deep kaolinitic weathering (etching) during the Jurassic and Cretaceous (Lidmar-Bergström, 1989, 1995). The peneplain was transformed into a landscape of joint aligned valleys or undulating hills with a relative relief in the fresh bedrock surface of between 20 and 200 m in the south and up to 400 m in the north. Abundant remnants of the old saprolites are preserved in connection with remnants of Jurassic and Cretaceous cover-rocks, but most of the saprolite had already been eroded during the Mesozoic and deposited as kaolinitic clays and quartz sand (Lidmar-Bergström, 1982).

The close relationship between the present relief in the Precambrian basement and the Mesozoic weathering front is well demonstrated in the old quarry at Ivö island in Lake Ivösjön, southern Sweden (Figure 1; Lidmar-Bergström, 1989). The quarry is situated on the northern slope of a residual hill, where the Mesozoic kaolinitic saprolite has been preserved below Cretaceous cover-rocks. In the upper part of the quarry the Cretaceous cover-rocks rest directly on the unweathered basement. The detailed shape of the granitic basement here is similar to roche moutonnées (Figure 3), though it has never been in touch with any ice cover. The steep hillside

Figure 3. Exhumed sub-Cretaceous forms, Ivön. The rounded shape is similar to roche moutonnées but 10 m of Cretaceous limestone was still covering the basement surface when the quarry was opened in 1884. This is the upper part of the rock in Figure. 4.

Figure 4. The Ivö quarry. The steep hillside is the Mesozoic weathering front. It was exposed by commercial quarrying for kaolin. The uppermost part of the rock was first exposed in the Cretaceous and thereafter both the fresh rock surface and the kaolinitic saprolite were covered by Upper Cretaceous strata.

continues below the *in situ* kaolin (Figure 4), which clearly demonstrates that the hillsides in this area were formed by deep weathering and subsequent stripping and not by glacial erosion. The forms of these granitic hills are determined largely by sheeting and fracturing (Magnusson and Lidmar-Bergström, 1983). Their Cretaceous surface is slightly undulating and weathering pits of different sizes and shapes are common. It is an important reference surface for studies of glacial erosion.

Tertiary plains with residual hills

Those parts of the Mesozoic etch-surfaces which were exposed to denudation during the Tertiary were transformed into plains with residual hills. Erosion also affected those areas of the sub-Cambrian peneplain which were uplifted and re-exposed during the Tertiary. Maximum denudation from the sub-Cambrian peneplain to the present surface amounts to 200 m within the South Swedish Dome and to between 400 and 600 m in northern Sweden (Lidmar-Bergström, 1995, 1996). The main erosion during the Tertiary was probably achieved by stripping of old kaolinitic saprolites, lateral retreat of slopes (pedimentation), and also by valley incision and renewed etching. Gravelly saprolites are common. So far, only one area in southeast Sweden has been investigated in detail. There, about 35 sites with remnants of gravelly saprolites have been encountered (Figure 1). The saprolites are clearly pre-Weichselian and probably mainly pre-Quaternary (Lidmar-Bergström *et al*., 1996).

GLACIAL EROSION OF THE BASEMENT

Estimates of glacial erosion

In well preserved parts of the sub-Cambrian peneplain, the erosion below the peneplain level is up to 20–30 m (maximally 40 m along valleys, Figure 2b). The relief is partly caused by stripping of the original thin kaolinitic saprolite after exposure. As remnants of Late Tertiary/Early Pleistocene saprolites are common in some areas, weathering to gravel is thought to be responsible for at least 10 m, and the glacial erosion of the fresh bedrock may account for only 5–10 m. The situation is a little different on upstanding residuals such as

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(b)

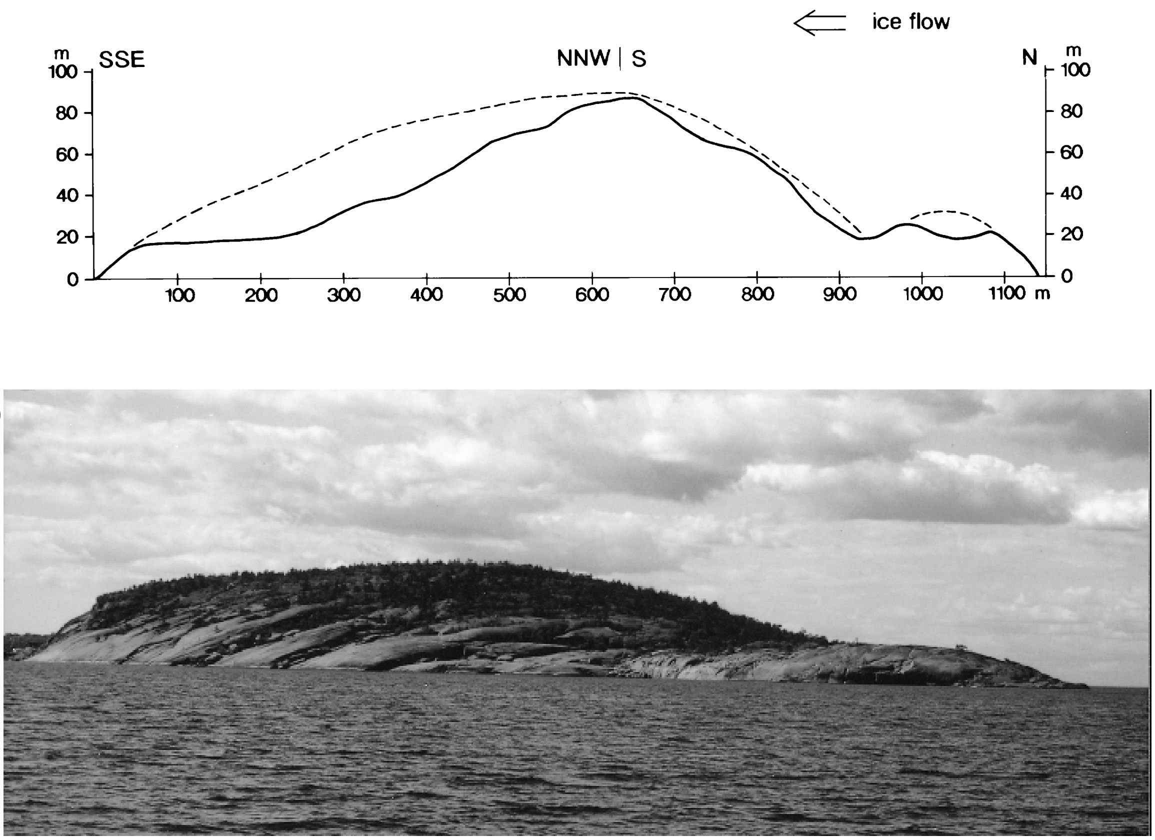

Figure 5. Profile across the island of Jungfrun, a granite dome. Its shape is determined by the old sheeting forming a large and a small dome. The profile is constructed from a contour map by Lundqvist (1920). It partly follows the sheeting (see (b)) and a rough estimation of the preglacial surface with preserved sheets is indicated. Glacial erosion has caused partial removal of sheets and plucking on the lee side. (b) The island of Jungfrun with the small dome to the right and the upper slope of the plucked lee side to the left. Note the sheeting. Ice movement from the right.

Jungfrun. This island is formed in a granitic intrusion (1400 Ma). The granite is sheeted. The sheeting was there already in the Cambrian since a sandstone with the same matrix as the surrounding Cambrian sandstone is found between the sheets (Mattsson, 1962). The lee side of the island is plucked by glacial erosion, but plucking has also occurred on the stoss side. Up to 30 m of rock has been removed in this way (Figure 5). The sheeting and fractures of the granite were important in facilitating glacial erosion (Mattsson, 1962).

Within the exhumed sub-Mesozoic relief the hills are often described as drumlins, but the cores of the drumlins are residual granitic hills left behind by Mesozoic deep weathering and subsequent stripping. Till covers on stoss and lee sides contribute to the drumlin form. Granite surfaces exposed to glacial erosion have been more or less transformed. The summit rocks of Kjugekull, a small Mesozoic residual hill, all show signs of heavy glacial erosion (Figure 6). Further down the hill, there is evidence of less glacial erosion (10–20 cm). One good example is a sheet surface that still retains Cretaceous weathering pits (Figure 7). Thus there is no glacial erosion of the granite surface on the lower parts of the hillsides, and maybe up to a couple of metres on the summit surfaces, where bedrock sheets have been plucked. Glacial erosion has often not reached the weathering front in this area. For example, the height difference between the summit of the residual hill Ivöklack and the deepest part of the surrounding lake basin is less (177 m) than between the hill summits and the fresh, unweathered bedrock below the saprolite (217 m; Nilsson, 1966).

The remnants of the gravelly saprolites within the Tertiary relief in southern Sweden are all in positions protected from glacial erosion. They can be at least 10 m thick and probably more (Lidmar-Bergström *et al.*, 1996). It seems likely that glacial erosion is the main cause of the stripping of these saprolites.

Figure 6. Glacially eroded summit of the exhumed sub-Cretaceous residual hill, Kjugekull, Ivö area. The glacially polished rocks show almost the original sheet planes. The rock surface was probably exposed by removal of overlying rock sheets. View from the east. Ice movement from the right.

In southern Sweden, channelled erosion has reached depths of up to 50 m and somewhat more in a few lake basins (Lindkvist and Danielsson, 1987). But most of the lake basins in the south are shallow and the role of the glacial erosion was restricted to removal of saprolites, as suggested by Nathorst (1879). Glacial erosion has been most effective along the valleys within the Scandinavian Highlands. A series of lake basins with a maximum depth of 220 m (Lindkvist and Danielsson, 1987) has been eroded in the Precambrian basement along the Highlands.

Roche moutonnée-like forms

As mentioned above, roche moutonnée-like forms lacking a clear plucked lee side are common on the exhumed surfaces. The more domed the shape, the more likely that it is a preglacial form (Lindström, 1988). The flatter varieties seem to be sheet planes exposed by plucking of overlying rock sheets (Figure 6).

GLACIAL EROSION OF COVER-ROCKS

How widespread was the blanket of cover-rocks before the onset of the glaciations and to what degree is the exhumation of the old surfaces due to glacial erosion? It is not easy to judge, but some observations can be presented.

The South Småland Peneplain truncates the sub-Cretaceous relief in the southeast. This truncation is erosional and preglacial as local relief, inclination of the surfaces, and saprolite remnants change at the border between the two surfaces. The preserved characters of the different palaeosurfaces speak strongly against heavy glacial erosion as the main cause of exhumation. Locally, however, glacial erosion in the cover-rocks has been important. The lake basins around Ivö island are formed by glacial erosion of the Cretaceous cover and probably also of underlying saprolite. In these channels the glacial erosion amounts to about 30–40 m. Glacial plucking has also affected boulders of Precambrian rocks in the Upper Cretaceous bottom conglomerate, which

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(b)

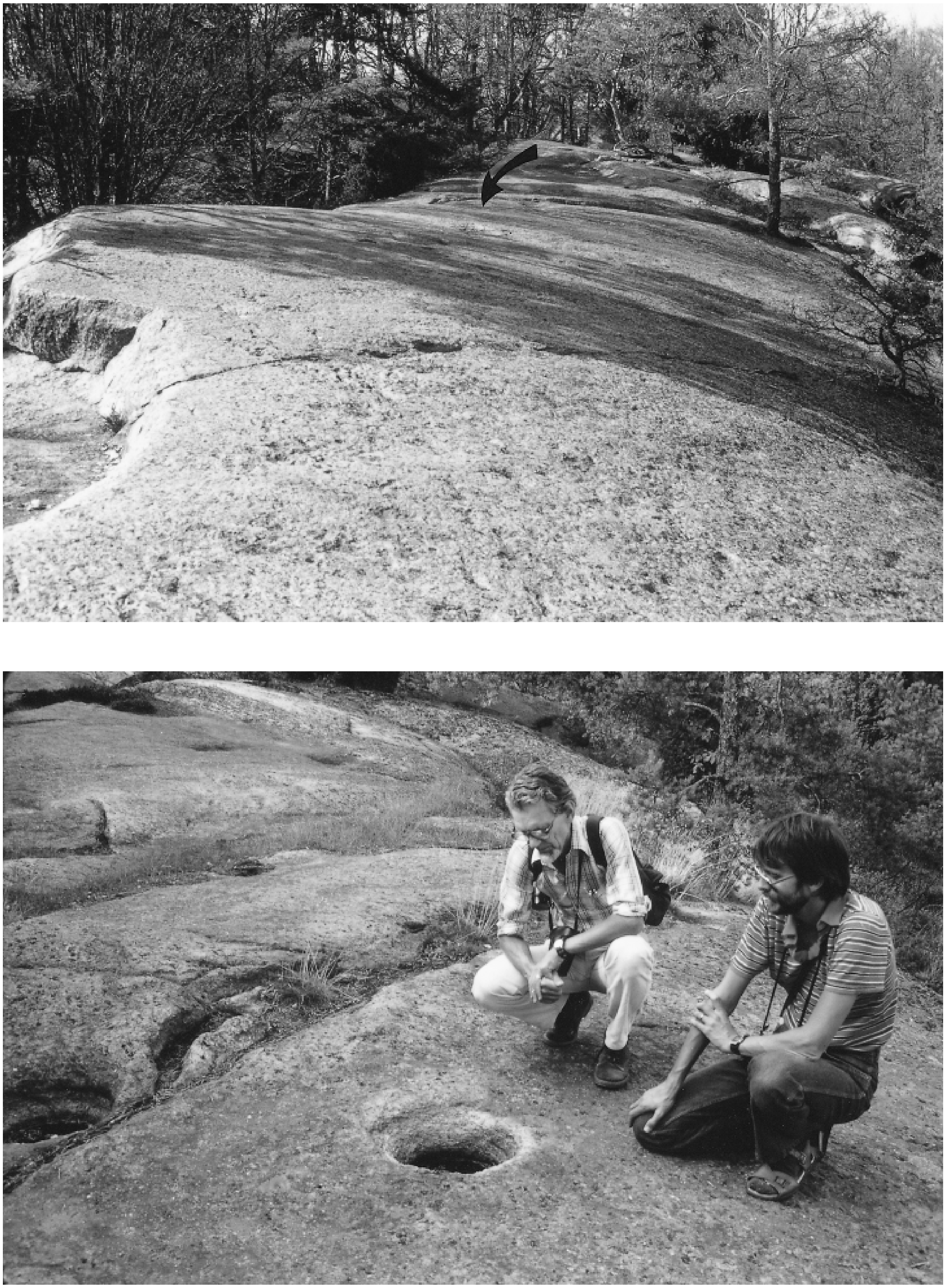

Figure 7. (a) Faint glacial polishing of exhumed sub-Cretaceous rock surfaces, Kjugekull, Ivö area. Remnants of the Cretaceous cover is preserved in the gorge to the left. Note glacial plucking in the lower left corner. Location of (b) is indicated by arrow. (b) Though glacially polished, the rock surface still retains sub-Cretaceous weathering pits. Glacial erosion amounting to about 10–15 cm can be estimated.

occur on the sides of the residual hills. These boulders are mainly dropped close to the hills in the south and west but a few have been encountered up to 50 km to the south of their original positions. They are easy to recognize because of their rounded forms and, in some cases, Cretaceous weathering pits.

Close to Cretaceous outcrops the till contains both Cretaceous limestone and flint. In other areas there are only flints within the till. They are often weathered slightly red and were interpreted as a Tertiary weathering residue (Lidmar-Bergström, 1982). Thus the erosion of the cover was here interpreted as preglacial. Redeposited, well preserved Late Tertiary plant remains are also encountered in the till (Kornfält and Bergström, 1984), which points to a mainly Late Tertiary exhumation.

In summary, glacial erosion of cover-rocks has occurred, but to a limited degree. The exhumation of the once-covered surfaces seems to be mainly of Late Tertiary age.

POSTGLACIAL WEATHERING AND EROSION

Granular disintegration has affected the glacially polished surfaces within the sub-Cretaceous relief in south Sweden. The weathering is up to 2 cm deep (cf. Swantesson (1992), southern Sweden; André (1995), northern Sweden). Aplite veins are less weathered and have the best preserved striae and crescentic marks and thus show the original glacial surface. Erosion of the last remnants of Cretaceous cover-rocks has also been achieved by postglacial wave abrasion along the sides of the upstanding residual hills. Valley incision has been reactivated in certain settings within the Highlands by glacial lowering of valley floors (Kleman and Stroeven, in press).

DENUDATION IN A LONG TIME PERSPECTIVE

A rough calculation of the denudation of the Precambrian basement during different time intervals and by different agents is given in Table I. Most of the denudation of the Precambrian rocks had occurred already by the end of the Proterozoic. The Precambrian rocks at the present surface were once formed at a depth of 15–20 km (Koark *et al*., 1978). The sub-Cambrian surface was the end result of the Precambrian denudation. It was protected for long time periods by a Palaeozoic cover and re-exposed at different times in different areas (Lidmar-Bergström, 1995). The denudation during the Mesozoic and Tertiary has been calculated with the use of the sub-Cambrian peneplain as a marker level. Glacial erosion has been roughly calculated in relation to the identified palaeosurfaces. The deepest glacial erosion in the Precambrian rocks has occurred in valleys along the Highlands, where channelled erosion has caused erosion of more than 200 m in certain settings. For most of the basement areas the glacial areal scouring is roughly estimated as being between 0 and 30 m in fresh bedrock. Channelled erosion might amount to 50 m or slightly more.

Table I. Calculated denudation of Precambrian basement during different time intervals and by different agents

Time	Process	Amount of erosion in the Precambrian basement
Proterozoic	Fluvial erosion, etching/sheet wash	Several kilometres; end result: sub-Cambrian peneplain
Mesozoic/Tertiary	Etching/stripping, pedimentation, valley incision	Up to between 400 and 600 m
Pleistocene	Glacial erosion, channelled	Over 50 m south Sweden, over 200 m north Sweden
Pleistocene	Ice sheet erosion in fresh bedrock	Up to some tens of metres
Pleistocene	Glacial erosion of saprolites	Up to between 10 and 50 m
Holocene	Surface weathering	About 2 cm

CONCLUSIONS

Most of the denudation within the Fennoscandian shield occurred in the Precambrian and can be counted in kilometres. Mesozoic and Tertiary deep weathering with subsequent stripping was of the order of hundreds of metres, while the Quaternary glacial erosion can be counted in tens of metres. In detail the variations are large, including areas with heavy glacial erosion up to a few hundreds of metres and areas with no glacial erosion at all. Postglacial erosion is of minor or local importance.

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